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AN INVESTIGATION OF THE EFFECT OF FLUID INJECTION ON THE SKIN-FRICTION COEFFICIENT OF AN INCOMPRESSIBLE TURBULENT BOUNDARY LAYER

By

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March 1969

U. S. ARMY AVIATION MATERIEL LABORATORIES
FORT EUSTIS, VIRGINIA

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Aerophysics and Aerospace Research Report 89

By

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ABSTRACT

The skin-friction reduction of an incompressible, turbulent boundary layer due to fluid injection was found in a porous pipe in the pipe Reynolds number range of 68,000 to 201,500. A reduction in C_F of approximately 20 percent was found with fluid injection quantities of $v_o/\bar{u}$ = .0004. The experimental results from the porous pipe agreed with the directly measured shear results on a flat plate by Roberts and Randall and agreed reasonably well with the results of Mickley and Davis. The experimental results gave a larger reduction in skin friction with fluid injection than predicted by theoretical analyses.

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LIST OF SYMBOLS

A	pipe cross-sectional area, ft^2
C	pipe circumference, ft
C_F	average skin-friction coefficient, nondimensional
C_{F_o}	average impervious skin-friction coefficient, nondimensional
D	pipe diameter, ft
F	injection parameter ($v_o/\bar{u}$ or v_o/U_∞), nondimensional
L	distance between Position 1 and Position 2, ft
P	pressure, lb/ft^2
R	pipe radius, ft
R'	distance along the pipe radius measured from the center line, ft
R_p	pipe Reynolds number, nondimensional
R_x	flat-plate Reynolds number, nondimensional
U	velocity at pipe center line, ft/sec
U_∞	free-stream velocity, ft/sec
u	velocity in the boundary layer, ft/sec
$\bar{u}$	pipe mean velocity (volumetric flow rate divided by cross-sectional area), ft/sec
v_o	injection velocity, ft/sec
x	distance along pipe length, ft
y	distance along pipe diameter, ft
ϵ	mean diameter of the sand grains, ft
λ	average pipe skin-friction coefficient (equal to $4\ C_F$), nondimensional
ρ	fluid density, $slugs/ft^3$

τ_w skin friction at the surface, lb/ft^2

Subscripts

$_1$ entrance of porous pipe

$_2$ exit of porous pipe

1. INTRODUCTION

In recent years, the study of the turbulent boundary layer with fluid injection has been of considerable interest because of possible reductions in skin friction and increases in surface cooling. Pappas and Okuno (Reference 1) conducted experiments on a slender cone in the compressible flow region with air and helium injection and noted a significant decrease in the skin friction as a result of the fluid injection. Mickley and Davis (Reference 2) also realized a reduction in skin friction due to air injection. The first direct measurements of the effect of fluid injection on the skin friction of an incompressible turbulent boundary layer were performed on a flat plate by Roberts and Randall (Reference 3). A decrease in skin friction was observed which was larger than that predicted by Mickley and Davis from their velocity profile analysis and also larger than the predictions of Dorrance and Dore (Reference 4) and Rubesin (Reference 5).

Because of the experimental difficulties associated with the direct measurement of the skin friction with fluid injection (References 3 and 6), it was felt that additional experimental evidence was required, with the result that Randall (Reference 7) performed experiments in a porous pipe. The porous pipe was chosen because of the relative ease in which skin-friction data could be obtained from the pressure data in the pipe, even though it was realized that velocity gradients and restricted boundary layer growth in the pipe would present some problem when compared to flat-plate data.

The objectives of this report are to present the results of the porous pipe experiments and the results of the flat-plate experiments and to compare the results with the theories and predictions of other researchers.

2. POROUS PIPE EXPERIMENTS

Pipe flow is the simplest flow in which skin friction can be accurately measured, as the static pressure drop down an impervious pipe is a direct function of the skin friction. The major problem with porous pipe experiments is that with fluid injection, the mass flow inside the pipe is increased and the pipe flow is accelerated; however, the results can be corrected for acceleration to enable comparison with the flat-plate data. The argument that the flow in a pipe and the flow on a flat plate are very different and therefore cannot be compared has reasonable theoretical foundation; for example, the flow in a pipe is nowhere intermittent, whereas the boundary layer on a flat plate has a very non-steady outer region. However, Schubauer (Reference 8) notes that the distribution of turbulent energy in pipe flow is the same as in the fully turbulent part of the flat-plate flow. The arguments of the curved pipe surface and the constant thickness pipe boundary layer imply that one or both of the parameters mentioned therein will be included in the derivation of the corresponding inner law. Thus, the existing form of the inner law would not be universal for either pipe or flat-plate flow. This conclusion is repudiated, however, by a large amount of experimental evidence collected in the past (Reference 9). The conclusion is therefore reached that only one relationship exists describing both types of flow; thus, impervious flat-plate and pipe flows can be compared, and it seems reasonable that these grounds also exist for the injection case.

2.1. THEORETICAL CONSIDERATIONS

The surface shear which a fluid with constant density exerts in moving through a passage can be obtained by

measuring the static-pressure drop along the passage and the entrance and exit velocity profiles. If the passage is a pipe of constant cross-sectional area A and of length dx bounded by walls and the two cross sections, then the following expression is obtained:

$$\tau_w C = - A \frac{dp}{dx} - \frac{d}{dx} \int_A \rho u^2 dA \tag{1}$$

In a pipe with solid walls and under the condition of fully developed flow, the right-hand integral is independent of x and the term is zero. This can be written as Schlichting (Reference 9) prefers,

$$\tau_w = \frac{P_1 - P_2}{L} \frac{R}{2} \tag{2}$$

However, when a fluid is injected through the porous walls, the momentum integral over a flow cross section changes in the flow direction, and the integral must be retained. As mentioned previously, the fluid injection causes the flow to accelerate. However, if the injection along the pipe is a constant, the acceleration should be continuous, and a value of the skin friction can be determined on at least a steady-state basis. From Equation (1),

$$\tau_w = \frac{P_1 - P_2}{L} \frac{R}{2} - \frac{\rho}{2\pi RL} [(\int_A u^2 dA)_2 - (\int_A u^2 dA)_1] \tag{3}$$

Now,

$$\int_A dA = \int_0^R 2\pi R' dR' \tag{4}$$

and Equation (3) becomes

$$\tau_W = \frac{P_1 - P_2}{L}\frac{R}{2} - \frac{\rho}{RL}\left[\left(\int_0^R u^2R'dR'\right)_2 - \left(\int_0^R u^2R'dR'\right)_1\right] \quad (5)$$

The u in each case is the velocity at the particular radius R'.

2.2. APPARATUS AND EXPERIMENTAL PROCEDURE

The porous pipe was constructed by bonding eight porous felt sections together and sanding the resulting seams smooth to give the effect of a continuous porous pipe. The porous pipe was 16.08 feet long with an inside diameter of 4.125 inches and an outside diameter of 4.625 inches. A 2-foot-diameter inlet nozzle attached to a 14-foot length of fiber glass pipe was used to insure proper entrance conditions and fully developed turbulent pipe flow at the entrance of the porous pipe section (Figure 1). Three multitube rakes were inserted at the entrance, center, and exit of the porous pipe and connected to multitube manometers. Two venturi meters were also installed, one at the entrance and the other at the exit of the pipe, to obtain inlet and exit volumetric flow rates. An axial blower with speed control enabled mean velocities up to 100 feet per second to be obtained. Twenty static-pressure taps were installed along the porous pipe.

The impervious experiments were performed by enclosing the porous section with a leakproof shroud, which was checked by monitoring the entrance and exit venturis. The pressure drop down the pipe, the velocity profile at three positions in the pipe, and the inlet and exit mass flows were measured for a number of stabilized mean-flow conditions.

A wooden shroud with regulated inlet pipes equipped with venturi meters was used for the fluid injection experiments.

The static pressure in the pipe was lower than atmospheric pressure, thereby enabling air to be sucked into the porous pipe. The experiments were conducted over a range of pipe Reynolds numbers from 68,000 to 201,500. The entrance pipe Reynolds number was held constant, and the flow regulators were sequentially adjusted to allow different fluid injection flow rates through the porous test section.

2.3. DISCUSSION OF RESULTS

The velocity profiles shown in Figure 3 indicate that the flow in the pipe was fully developed. Figure 4 shows the impervious skin friction plotted versus pipe Reynolds number. A re-plot of this data, as shown in Figure 5, was made to enable a comparison with Nikuradse's sand-roughened pipe tests (Reference 9) to be made. The shape of the curve in Figure 5 is similar to Nikuradse's results, and the impervious pipe has a constant value of λ of 0.03. Although the relative roughness ϵ/D can be estimated directly from Nikuradse's plot, Powell (Reference 10) gives a plot of λ versus pipe diameter for constant ϵ's which allows a more accurate estimation. For the known λ and pipe diameter, the ϵ can be obtained by interpolation between the constant ϵ curves. The plot gives a result of $\epsilon/D = 1/197$ for the pipe used in the experiments.

Figures 6, 7, 8, and 9 are the nondimensional velocity profiles at positions 1 and 2 for a pipe Reynolds number of 184,936 at various injection velocities. The expected deformation of the flow due to fluid injection is apparent in these figures, with the greatest deformation naturally occurring at the greatest values of fluid injection. Most likely, the injected air causes, by displacement, an acceleration in the flow quite far away from the wall. It would therefore appear the assumption that the influence of fluid injection

is restricted to the lower portion of the boundary layer does not apply to pipe flow.

The static-pressure drop down the pipe tended to increase slightly as fluid injection was increased because of the acceleration of the fluid in the pipe due to fluid injection. The difference between the pressure drop terms and the momentum term, as given by Equation (5), is the surface shear from which the skin friction coefficient based on the entrance mean velocity was obtained. The skin-friction reduction in the form C_F/C_{F_o} against $v_o/\bar{u}$ for each pipe Reynolds number is plotted in Figure 10. Within the small range of pipe Reynolds numbers tested, it would appear that any Reynolds number effect falls within the scatter of the data. The maximum reduction in skin friction for the highest injection velocity was approximately 20 percent.

The scatter in the data presented in Figure 10 is most likely the result of difficulties in determining the momentum term in Equation (5). A planimetering technique was used; however, it must be realized that in many of the experiments, the change in momentum term was often of the same magnitude as the change in pressure term, thereby introducing the possibility of rather large errors.

3. POROUS FLAT PLATE EXPERIMENTS

Direct measurements of the surface shear on a porous flat plate with fluid injection were made using a balanced 8-inch-diameter element floating on mercury. The experiments were conducted in an adjustable-wall, open-circuit, subsonic wind tunnel, shown schematically in Figure 11. The wind tunnel floor contained a 3-foot test section of a porous surface constructed of very finely woven fiber glass material stretched over honeycomb. The porous test section including the floating element was aligned with the floor to within ±0.0001 inch per foot using a small laboratory level of that accuracy. The height of the floating element was adjusted by adding mercury to or removing mercury from the chamber in which the element was floating. The gap area surrounding the floating element was less than 2 percent of the total element area, which is within the acceptable limit as given by Haklinen (Reference 6). The calibrated measuring system was a linear variable differential transformer with a range of ±10.0 grams, which was positioned into minimum contact with the element. The element was pressure balanced by means of the flow deflectors to insure that the mass transfer through the surface did not displace the element with respect to the surrounding wall or contribute to a force in any direction. For each fluid injection condition, the pressure gradient over the porous wall and the floating element was checked to insure that flat-plate conditions prevailed. If such conditions did not exist, suitable adjustments were made by means of the cranks on the wall opposite the test section. The injection flow rate was controlled by the flow regulator and measured by the calibrated venturi meter.

To check the accuracy of the system, direct shear measurements were made for the impervious condition and were compared with published data from Schlichting (Reference 9).

Results of the experiments agreed with the published data to within approximately 5 percent. The fluid injection experiments were performed at a free-stream velocity of 57 feet per second and within a fluid injection velocity range of $v_o/U_\infty = 0.000133$ to $v_o/U_\infty = 0.00113$. If it can be assumed that the errors involved in the direct measurements are constant, then the effect of these errors is minimized by using the ratio of C_F/C_{F_o} instead of the absolute value of C_F. The final results showing an acceptable amount of scatter are shown in Figure 12, where C_F/C_{F_o} is plotted against v_o/U_∞. Possible errors in the data include alignment difficulty, possible gap effect, small pressure gradient deviation, and calibration error. To permit comparison with previous work, the data in Figure 12 were re-plotted in the form C_F/C_{F_o} versus $2F/C_{F_o}$ and compared with the theories of Rubesin, Dorrance and Dore, and Mickley and Davis (Figure 13).

4. COMPARISON OF EXPERIMENTAL AND THEORETICAL RESULTS

A comparison of the experimental results from the porous flat plate and the porous circular pipe with fluid injection can be made in Figure 14. It can be seen that, compared on a basis of $v_o/\bar{u}$, the direct shear results on the flat plate by Roberts and Randall agree quite well with the porous pipe data. Also shown in Figure 14 are the flat-plate experimental results of Mickley and Davis (Reference 2), which are dependent on a velocity profile analysis and which indicate a smaller reduction in skin friction coefficient for the same fluid injection parameter than either the flat-plate or the porous pipe results given in this report.

For convenient comparison with the flat-plate theoretical analyses of Dorrance and Dore (Reference 4) and Rubesin (Reference 5), the data are re-plotted in the form C_F/C_{F_o} versus $2F/C_{F_o}$ (Figure 15). Also re-plotted in this figure are the flat-plate results of Roberts and Randall and Mickley and Davis. Figure 15 clearly shows a wide variation in results which may be attributable to some extent to the method of presentation and to the assumptions used in the theoretical analyses.

Dorrance and Dore used a mixing length approach in their analysis of the turbulent boundary layer with fluid injection, in which they assumed that the turbulent boundary layer extended to the surface, thus denying the existence of the laminar sublayer. In addition, this method omits the contribution of molecular transfer in the region near the wall. Rubesin's approach included the existence of the laminar sublayer but made several assumptions to greatly simplify the mathematical solution of the boundary layer equations. This theory requires the joining of a mixing length hypothesis for the external portion of the turbulent boundary layer to

a completely laminar sublayer, and the solution is strongly dependent on the choice of the matching point. The results of each of these theoretical approaches differ with each other and differ considerably with the experimental data.

The wide variation in the experimental results in Figure 15 is not as apparent in Figure 14, which may be explained by the method of presentation favored by previous researchers, which includes the use of the term C_{F_o}. The impervious skin-friction coefficient varies depending upon the type of porous material used, something which is neglected in most analyses, with the result that the use of different porous materials with similar porosity characteristics yet different roughness factors causes the data to move to the right or left if the results are plotted in the form used in Figure 15. For example, if two data points are considered in a plot such as in Figure 15 at a fixed value of C_F/C_{F_o} and a fixed value of F, the data point with the highest impervious skin-friction coefficient will appear to move to the left of the other. Perhaps a better comparison of experimental results can be made with the data plotted in the form C_F/C_{F_o} versus $v_o/\bar{u}$.

5. CONCLUSIONS

The reduction in skin-friction coefficient due to fluid injection determined from the porous pipe experiments was in close agreement with the directly measured shear results on a flat plate measured by Roberts and Randall (Reference 3). The porous pipe results also compare favorably with the flat-plate results of Mickley and Davis (Reference 2).

The experimental results both on the flat plate and on the porous pipe give a larger reduction in skin-friction coefficient than that predicted by theoretical analyses; however, the three sets of experimental data agree reasonably well and as a group are distinctly separate from the theoretical results, which may indicate a need for a more complete theoretical analysis.

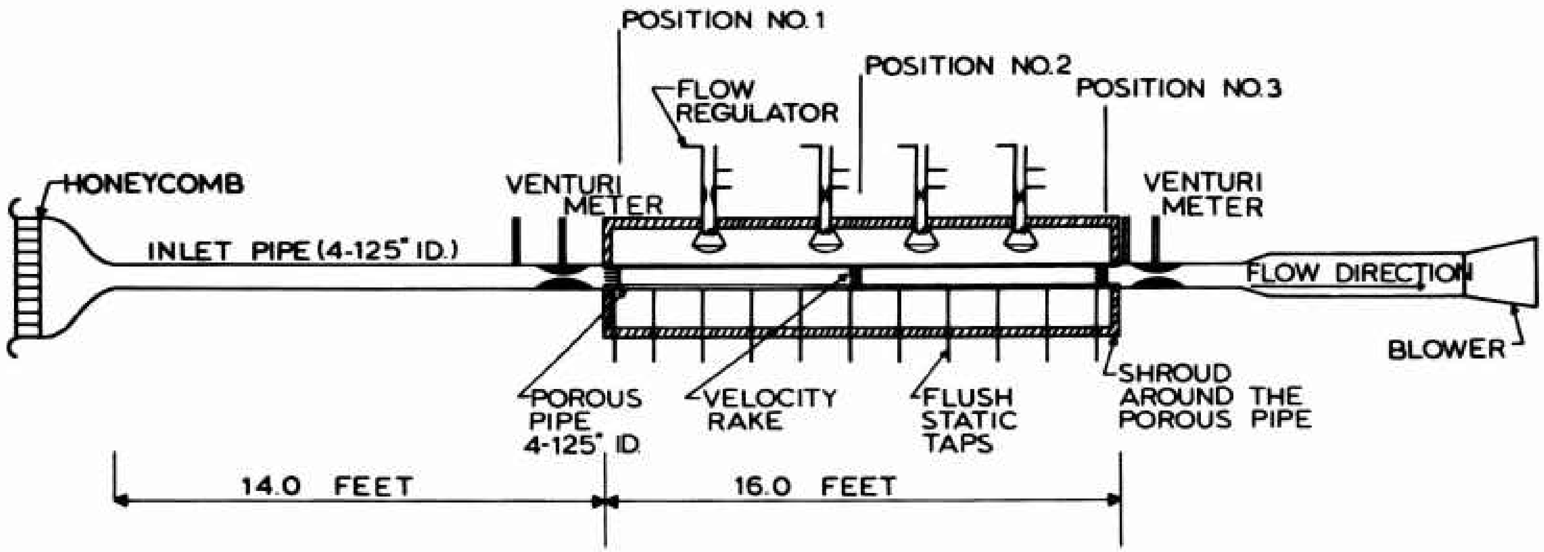

Figure 1. Schematic Drawing of the Porous Pipe Facility.

Figure 2. Porous Pipe Facility With the Shroud Over the Porous Pipe Test Section.

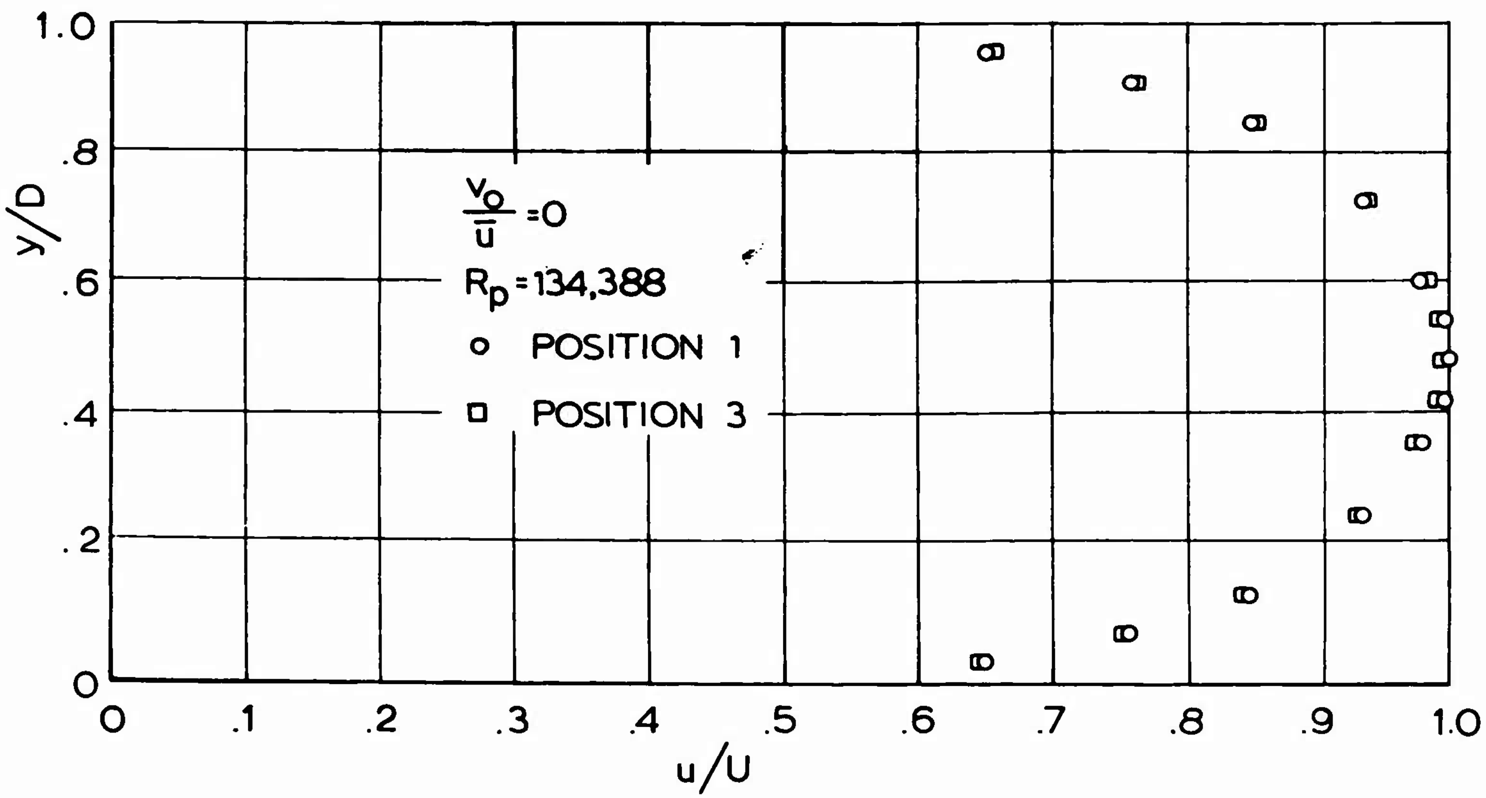

Figure 3. Velocity Profiles for the Impervious Pipe Condition $v_o/\bar{u}$, R_p = 134,388.

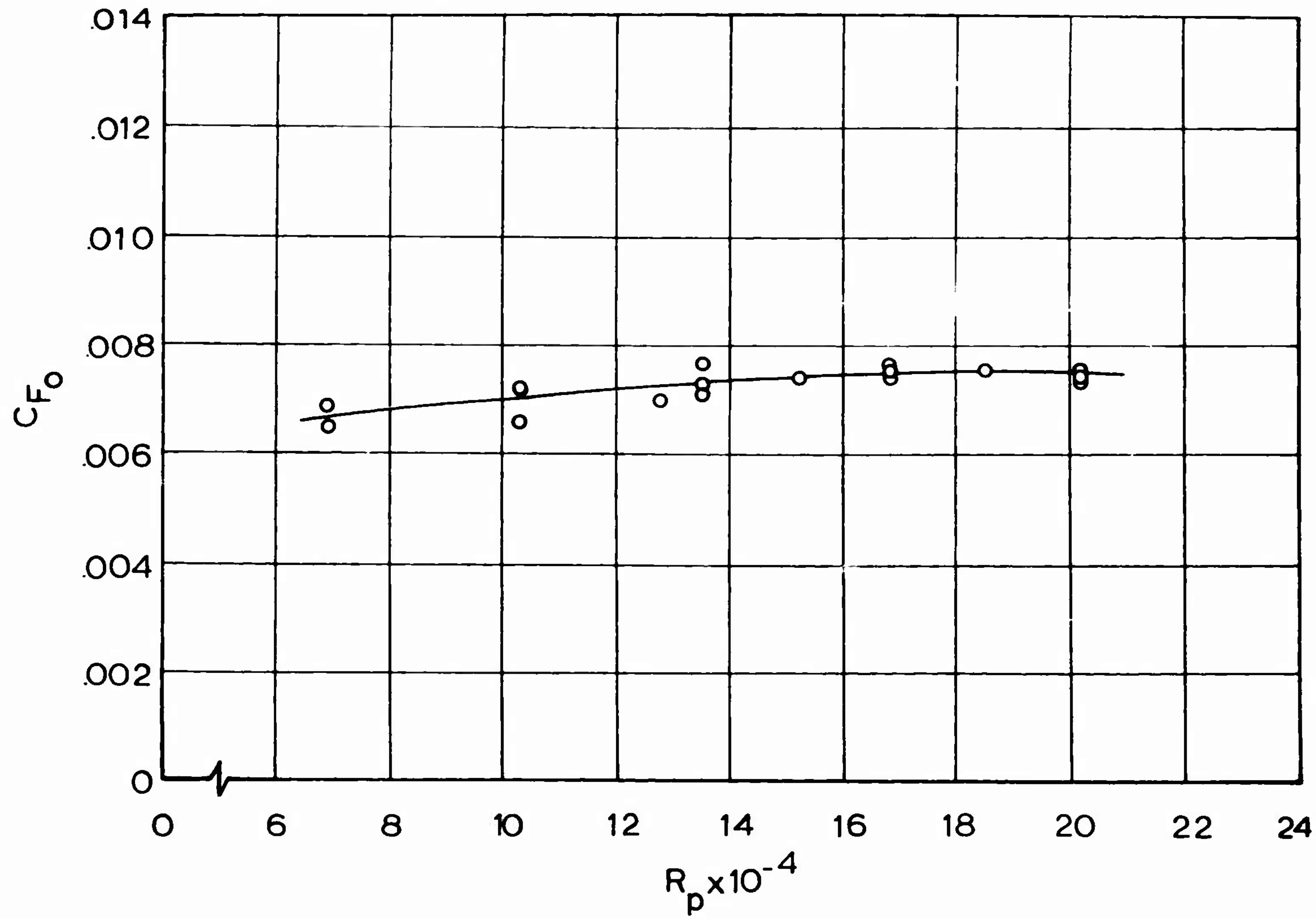

Figure 4. Impervious Pipe Skin-Friction Coefficient Versus Pipe Reynolds Number.

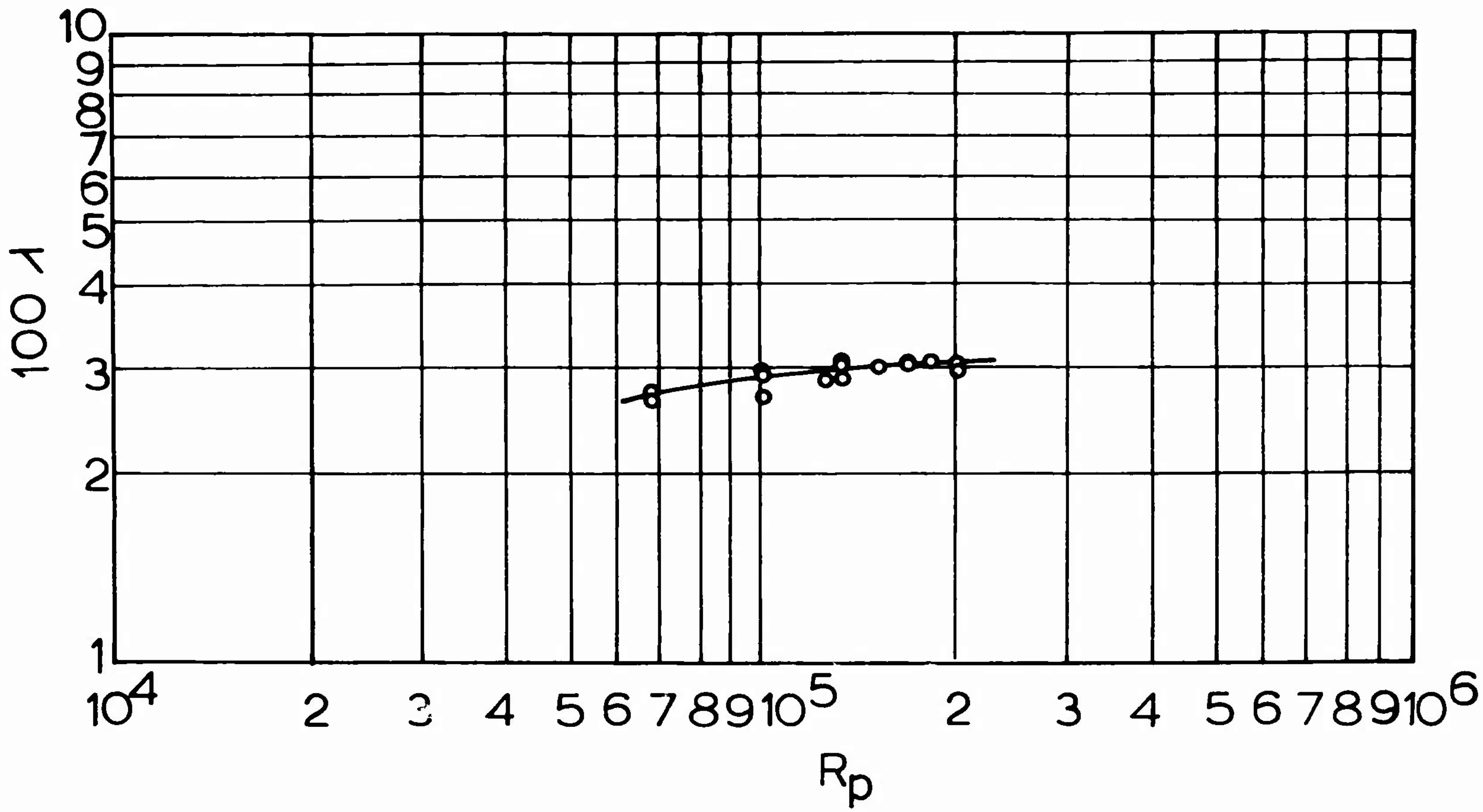

Figure 5. Pipe Skin-Friction Coefficient as 100 λ Versus Pipe Reynolds Number.

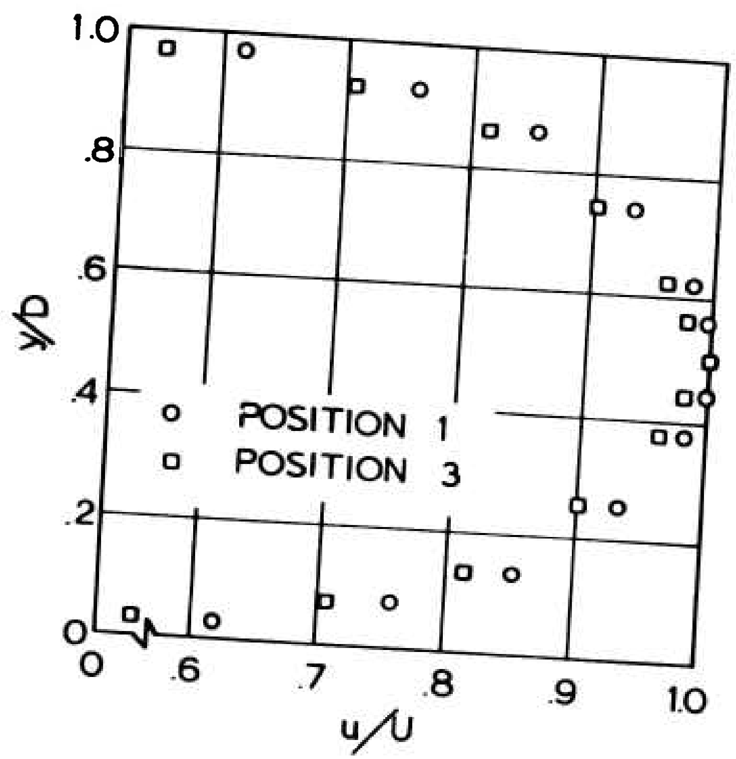

Figure 6. Velocity Profiles for Injection Condition ($v_o/\bar{u} \times 10^3 = .06824$), R_p = 184,936.

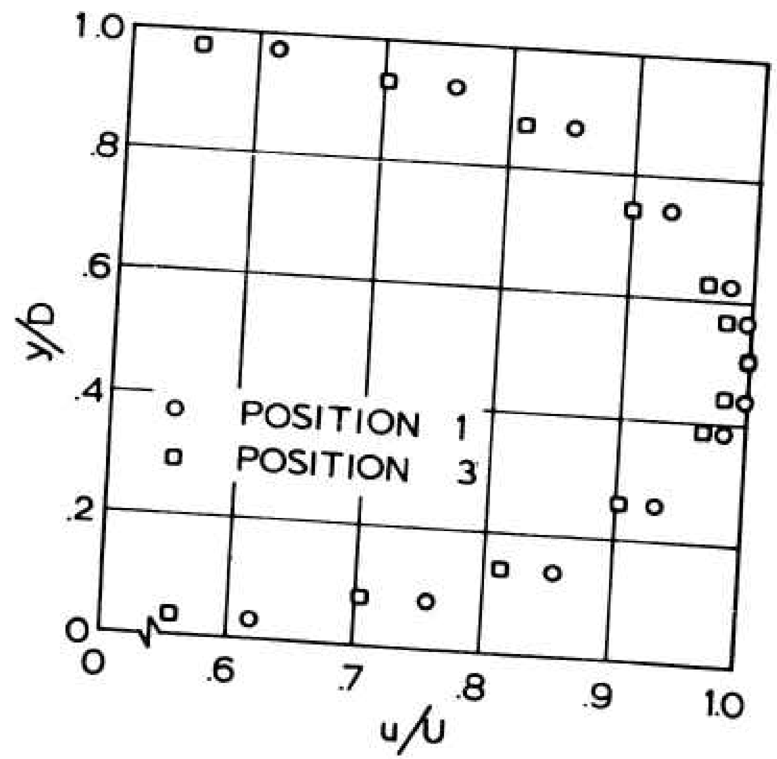

Figure 7. Velocity Profiles for Injection Condition ($v_o/\bar{u} \times 10^3 = .23309$), R_p = 184,936.

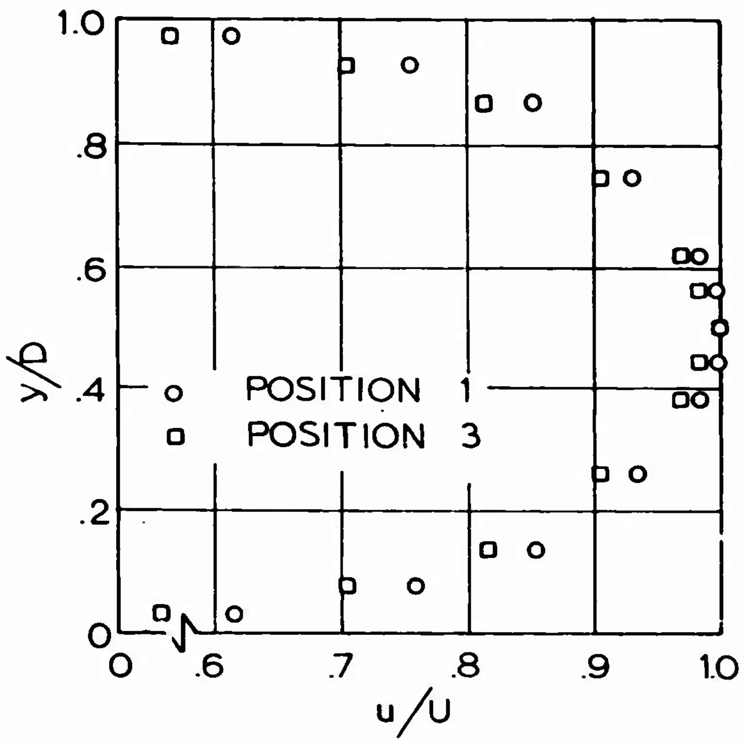

Figure 8. Velocity Profiles for Injection Condition ($v_o/\bar{u} \times 10^3$ = .32728), R_p = 184,936.

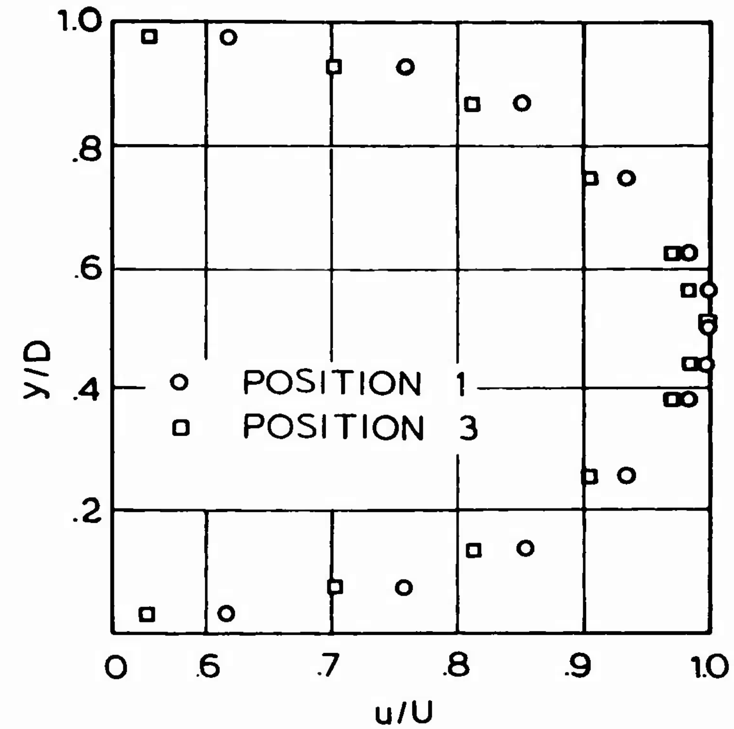

Figure 9. Velocity Profiles for Injection Condition (v_o $\bar{u} \times 10^3$ = .37806), R_p = 184,936.

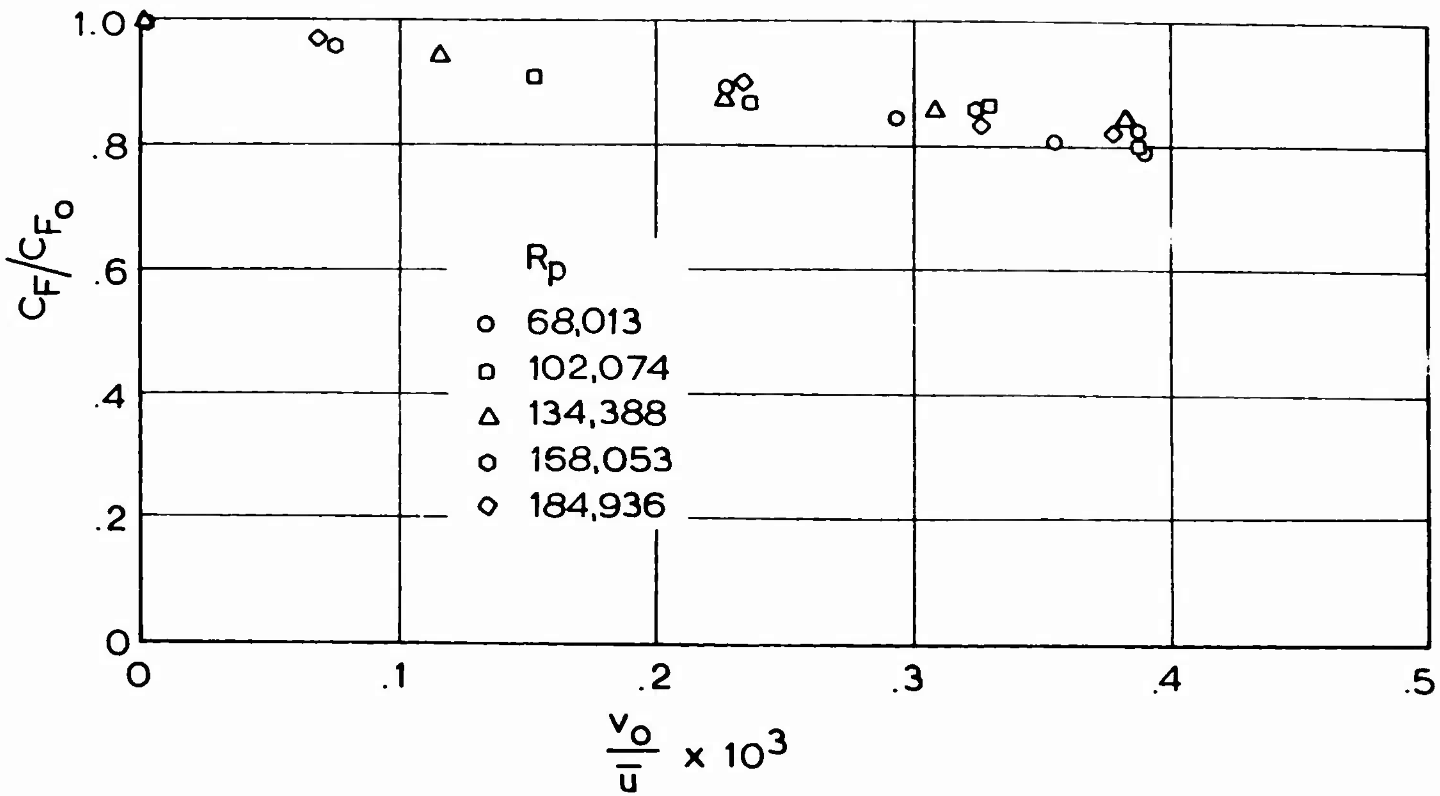

Figure 10. The Reduction of the Average Skin-Friction Coefficient With Fluid Injection in a Porous Pipe.

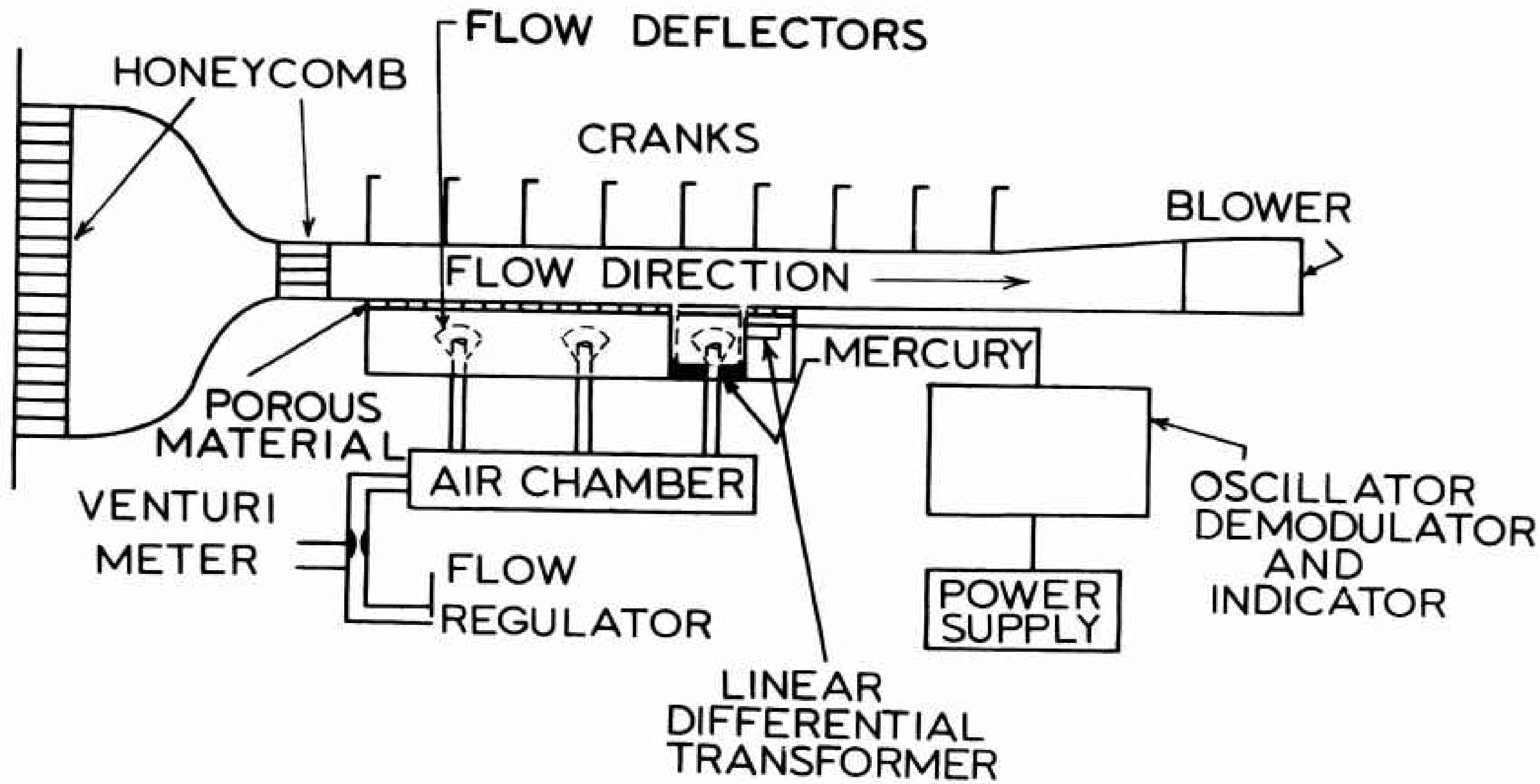

Figure 11. Schematic Drawing of the Boundary Layer Tunnel With the Floating Element.

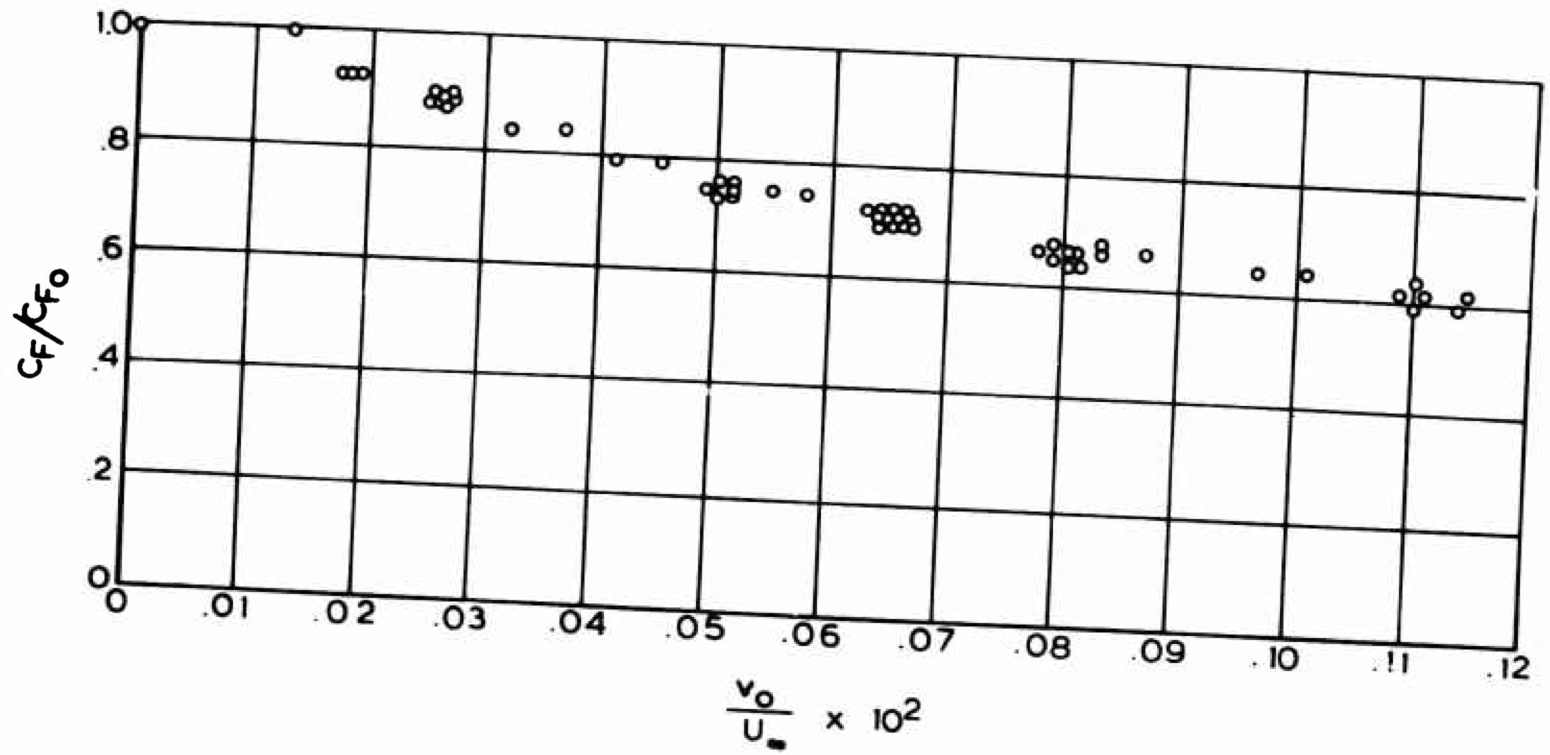

Figure 12. The Reduction of the Average Skin-Friction Coefficient With Fluid Injection for a Flat Plate.

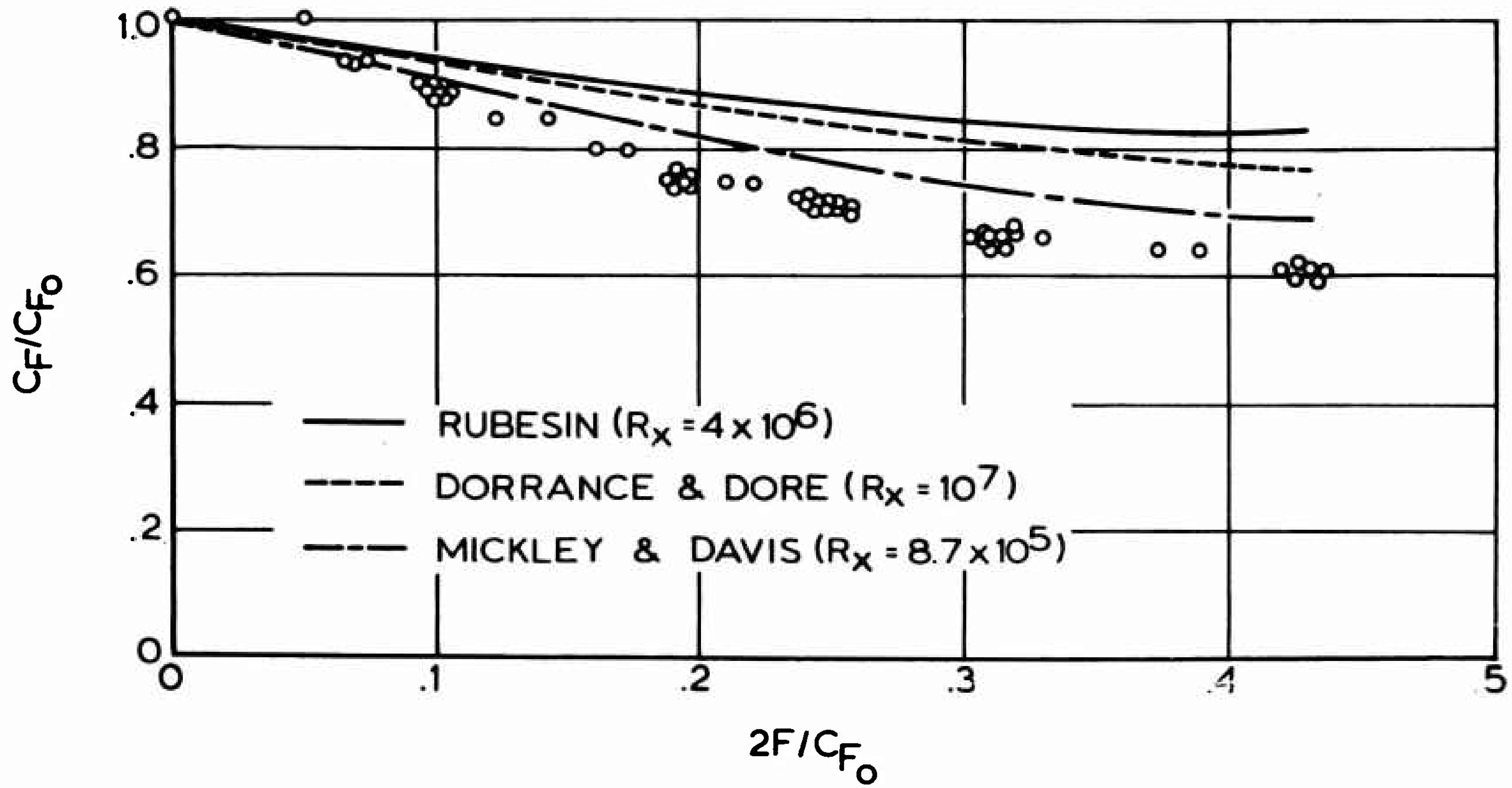

Figure 13. Comparison of Experimental and Theoretical Reduction of the Average Skin-Friction Coefficient With Fluid Injection for a Flat Plate.

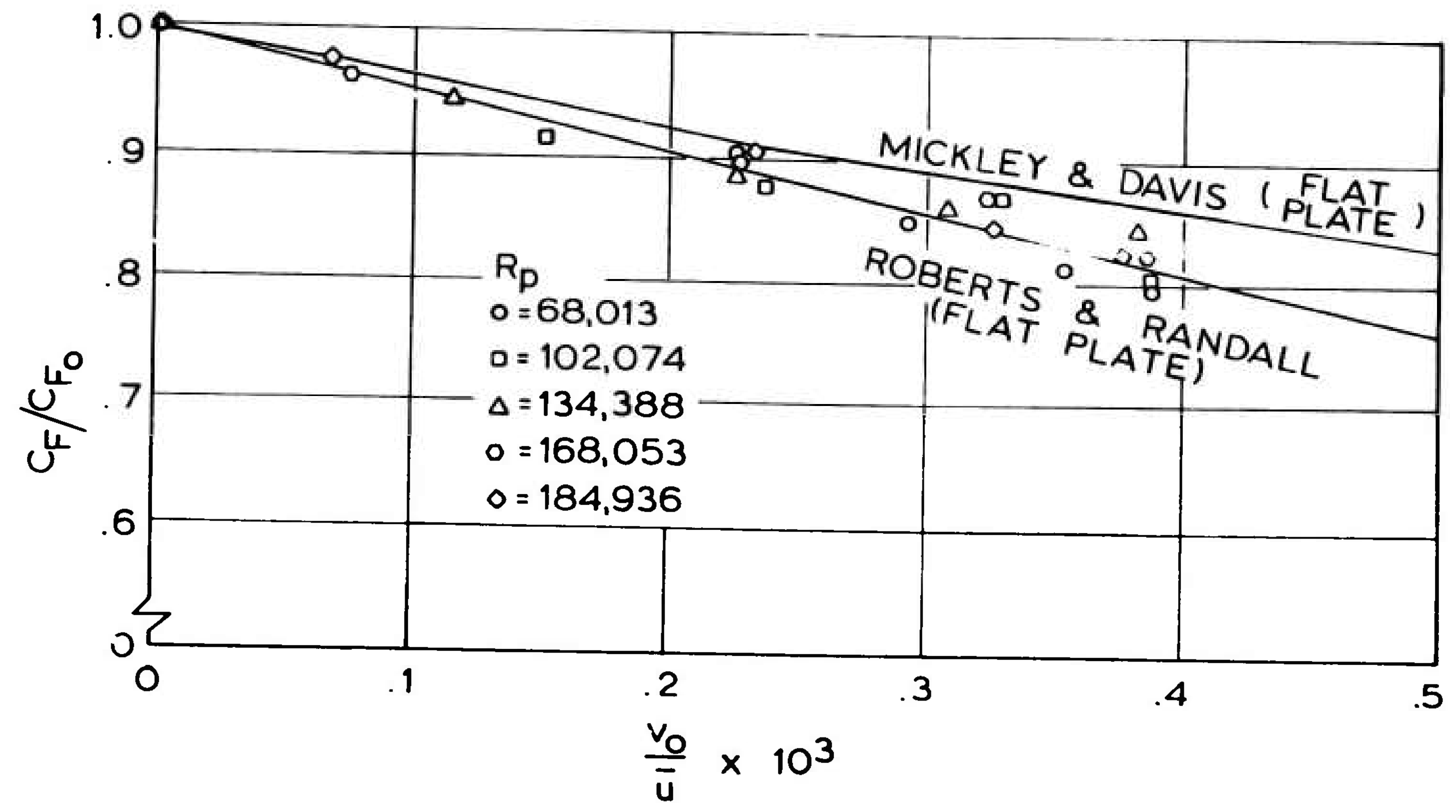

Figure 14. Comparison of the Experimental Flat-Plate Data With the Pipe Data on the Effect of Fluid Injection on the Skin-Friction Coefficient.

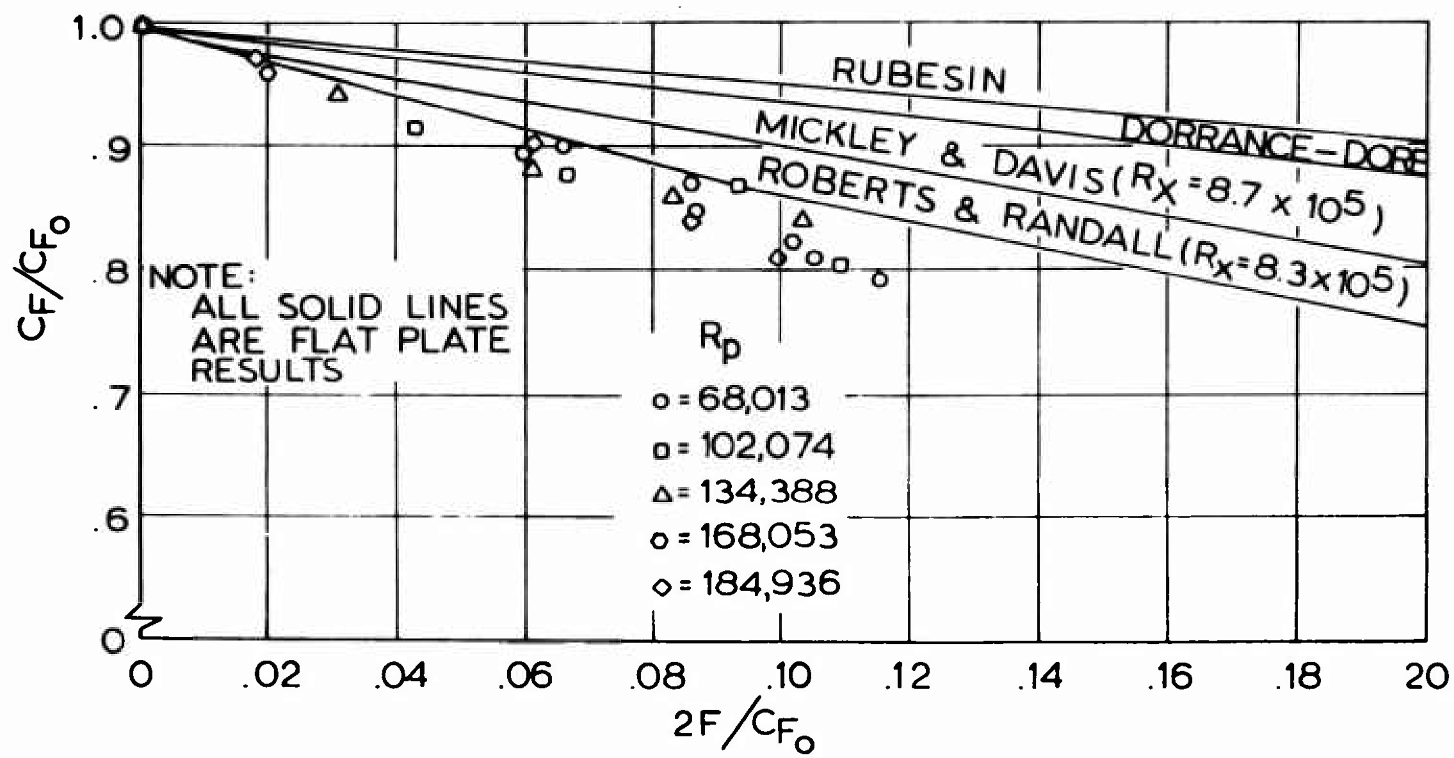

Figure 15. Comparison of Experimental and Theoretical Reduction of the Average Skin-Friction Coefficient With Fluid Injection.

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AN INVESTIGATION OF THE EFFECT OF FLUID INJECTION ON THE SKIN FRICTION COEFFICIENT OF AN INCOMPRESSIBLE TURBULENT BOUNDARY LAYER

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13. ABSTRACT

The skin-friction reduction of an incompressible, turbulent boundary layer due to fluid injection was found in a porous pipe in the pipe Reynolds number range of 68,000 to 201,500. A reduction in C_F of approximately 20 percent was found with fluid injection quantities of $v_0/\bar{u} = .0004$. The experimental results from the porous pipe agreed with the directly measured shear results on a flat plate by Roberts and Randall and agreed reasonably well with the results of Mickley and Davis. The experimental results gave a larger reduction in skin friction with fluid injection than predicted by theoretical analyses. ( )

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